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IOTA: (Integrable Optics Test Accelerator) Status and Plans

Vladimir Shiltsev, Fermilab

Workshop on “Plasma-based Accelerator Concepts for Colliders”
LBNL, January 6-8, 2016

IOTA in the DOE OHEP GARD Program

- **Recommendation 2.** Construct the IOTA ring, and conduct experimental studies of high-current beam dynamics in integrable non-linear focusing systems. (p. 9, 18)
  - GARD thrust: Accelerator and Beam Physics
- **Recommendation 3.** Support a collaborative framework among laboratories and universities that assures sufficient support in beam simulations and *in beam instrumentation to address beam and particle stability including strong space charge forces.* (p. 9, 17)
  - GARD thrust: Accelerator and Beam Physics

	Intensity Frontier Accelerators	Hadron Colliders	e^+e^- Colliders
Current Efforts	PIP	LHC	
	PIP-II	HL-LHC	ILC
Next Steps	Multi-MW proton beam	Very high-energy *pp* collider	1 TeV class energy upgrade of ILC*
Further Future Goals	Neutrino factory*	Higher-energy upgrade	Multi-TeV collider*

*dependent on how physics unfolds

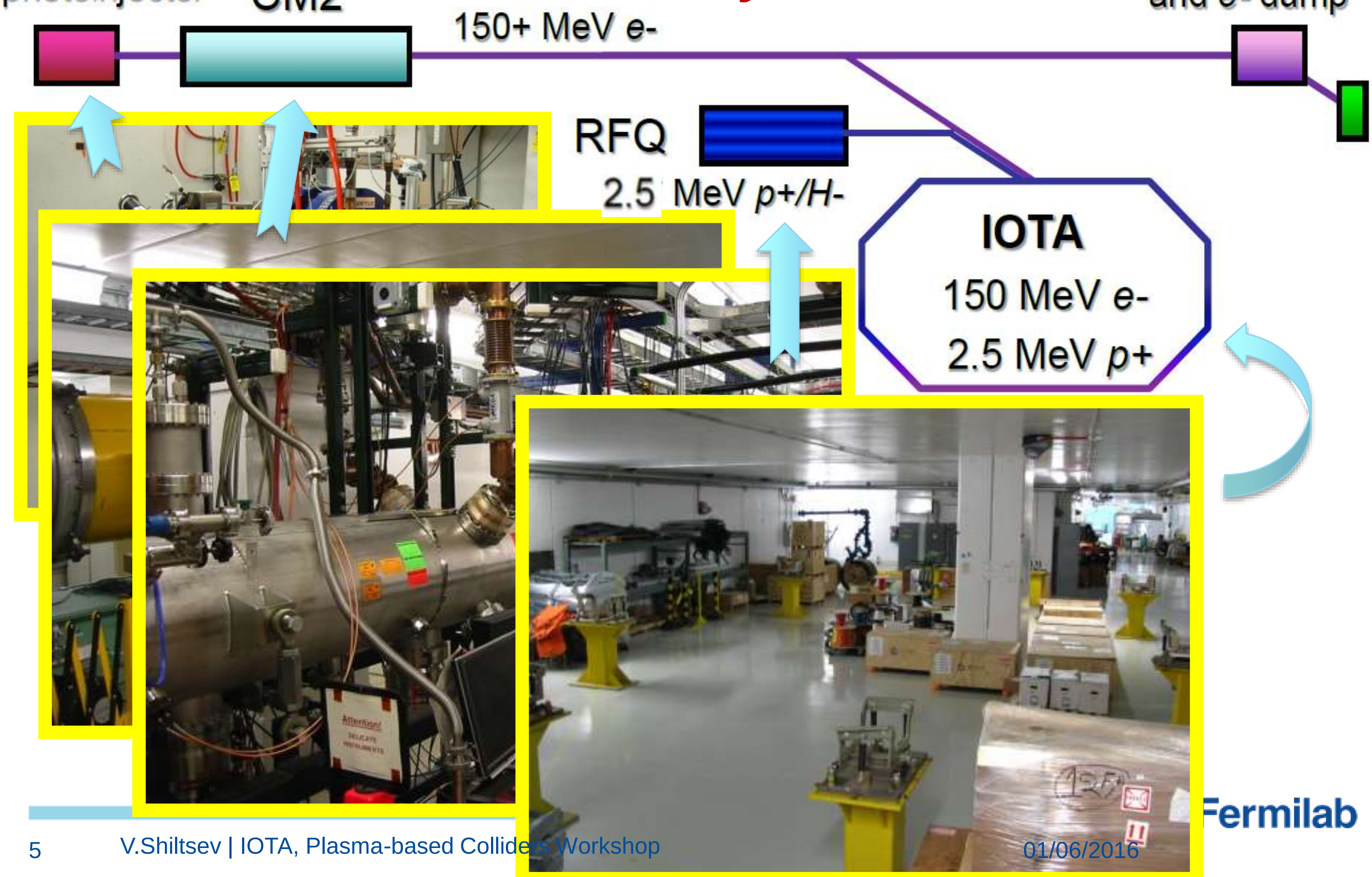
Overarching Motivation – R&D on Intensity Frontier Accelerators for HEP

- The future of Intensity Frontier HEP accelerators is in the beam control and mitigation of beam losses!
- To enable multi-MW beam power, losses must be kept well <0.1% at the record high intensity:
  - Need <0.06% for PIP-III (2.5 MW FNAL complex upgrade)
  - Present level ~3-5% in Booster and MI synchrotrons
  - (Very challenging after 50 years of development)
- Need to develop technology for
  - Space-charge countermeasures
  - Beam halo control
  - Single-particle and coherent beam stability

IOTA Physics Motivation

- To explore two **innovative ideas**:
  - *Integrable Optics*
    - *With strongly nonlinear magnets*
    - *With specially shaped electron beams in electron lenses*
  - *Space Charge Compensation*
    - *With ~"Gaussian" electron lenses*
    - *With neutralizing "electron columns"*
- Both work in simulations→ to test them experimentally, we are building the **Integrable Optics Test Accelerator (IOTA)**
  - a machine for proof-of-principle R&D
  - can operate with either *e*- or *p*+ up to 150 MeV/c momentum
  - large aperture,
  - significant flexibility of the beam optics lattice
  - precise control of the optics quality and stability
  - set up for very high intensity operation (with protons)

IOTA @ Fermilab Accelerator Science and Technology facility



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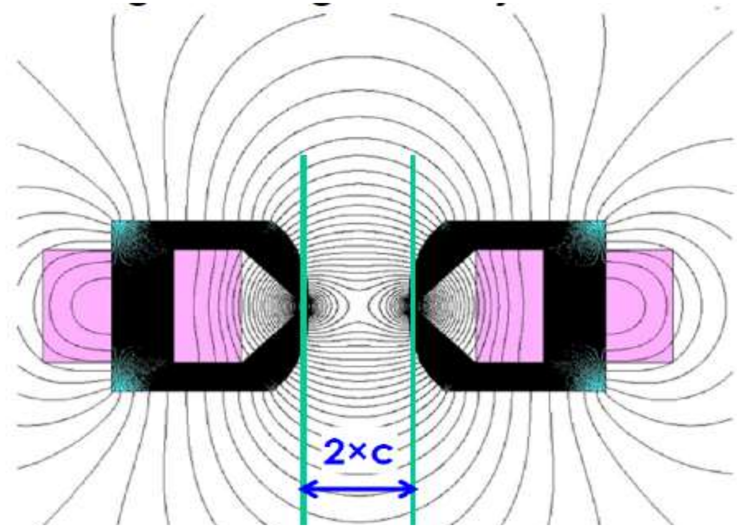
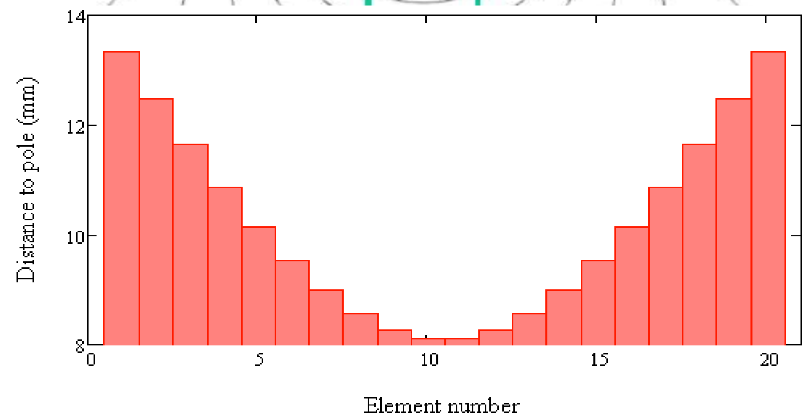
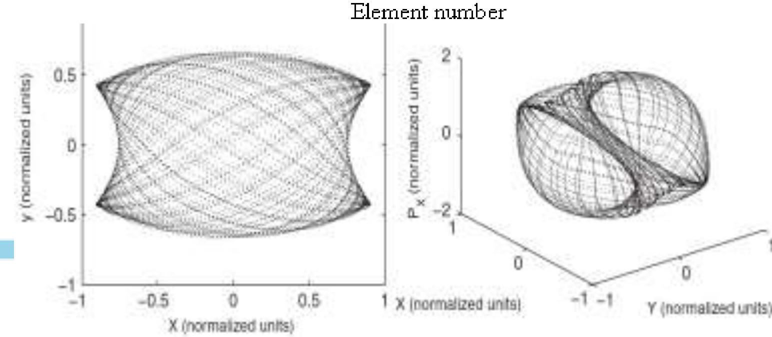
Integrable Optics with Non-linear Magnets

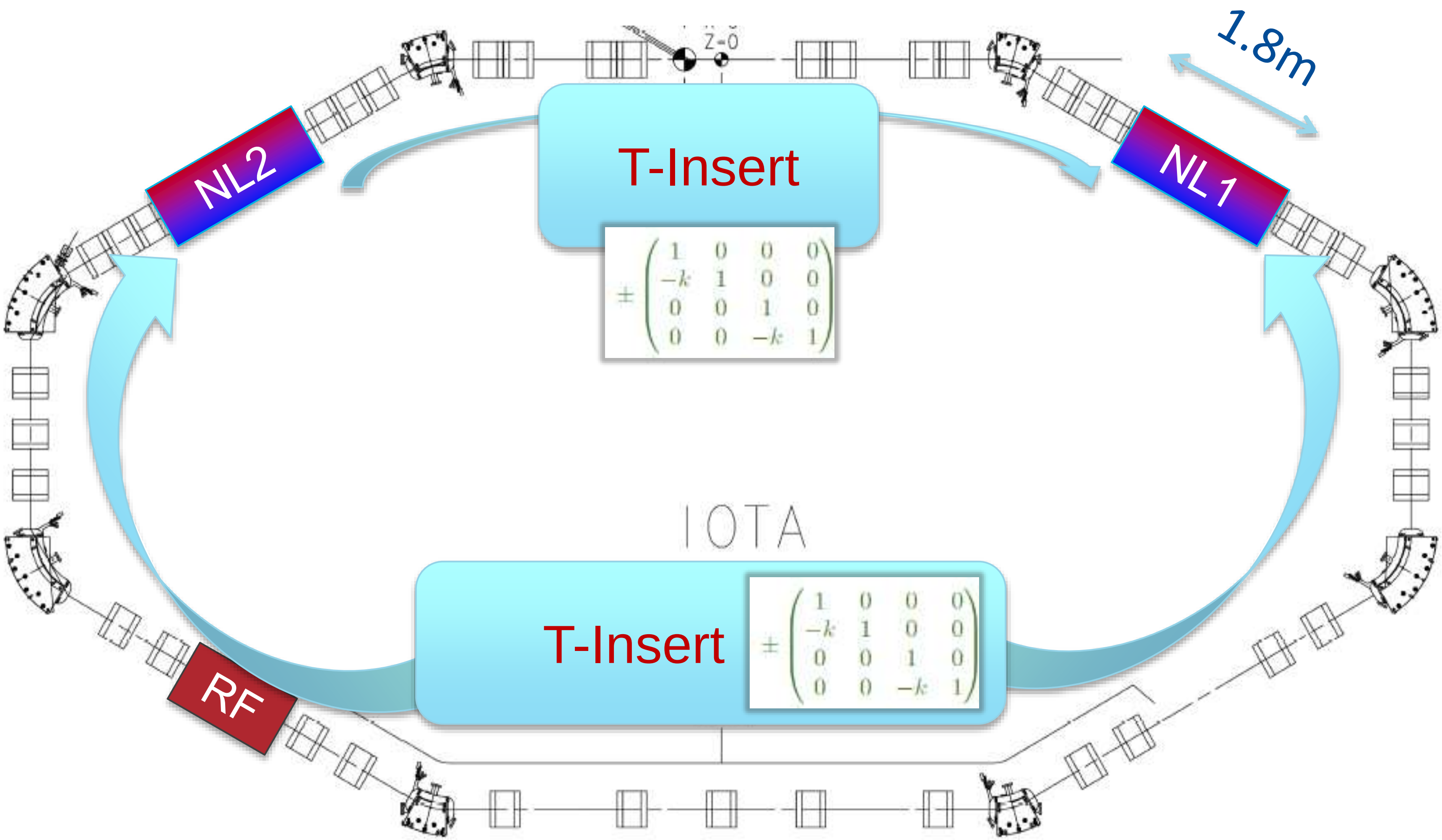
- Additional integrals of transverse motion possible:
  - Special NL magnets →
  - Special optics of the ring (next slide)
  - Special longitudinal shape of the magnets (gap vs Z) →
  - Makes particle dynamics stable with very large tune-spread
    - Danilov, Nagaitsev, PRSTAB **13**, 084002 (2010) →







IOTA Optics with Two Nonlinear Lenses

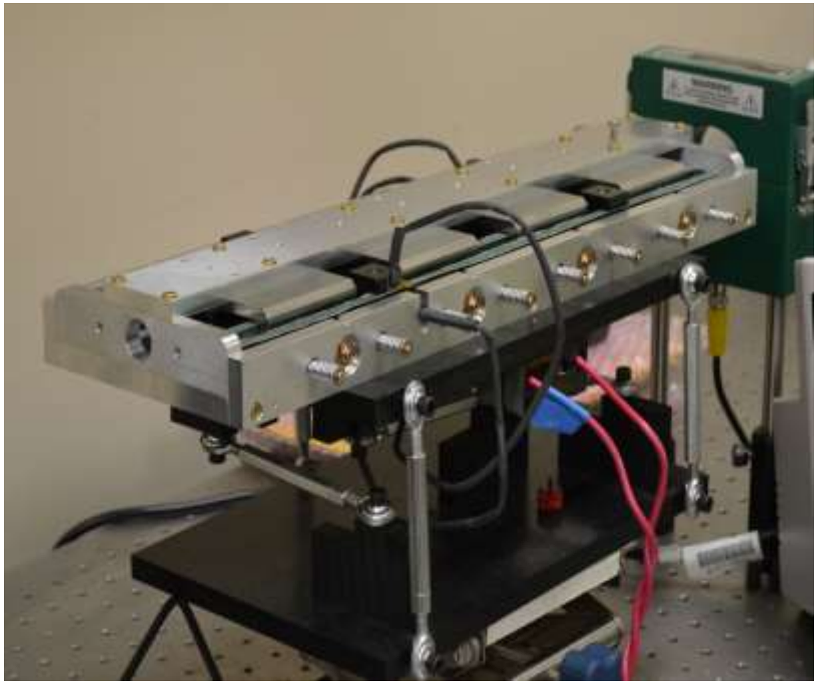


$$\pm\begin{pmatrix}1&0&0&0\\-k&1&0&0\\0&0&1&0\\0&0&-k&1\end{pmatrix}$$

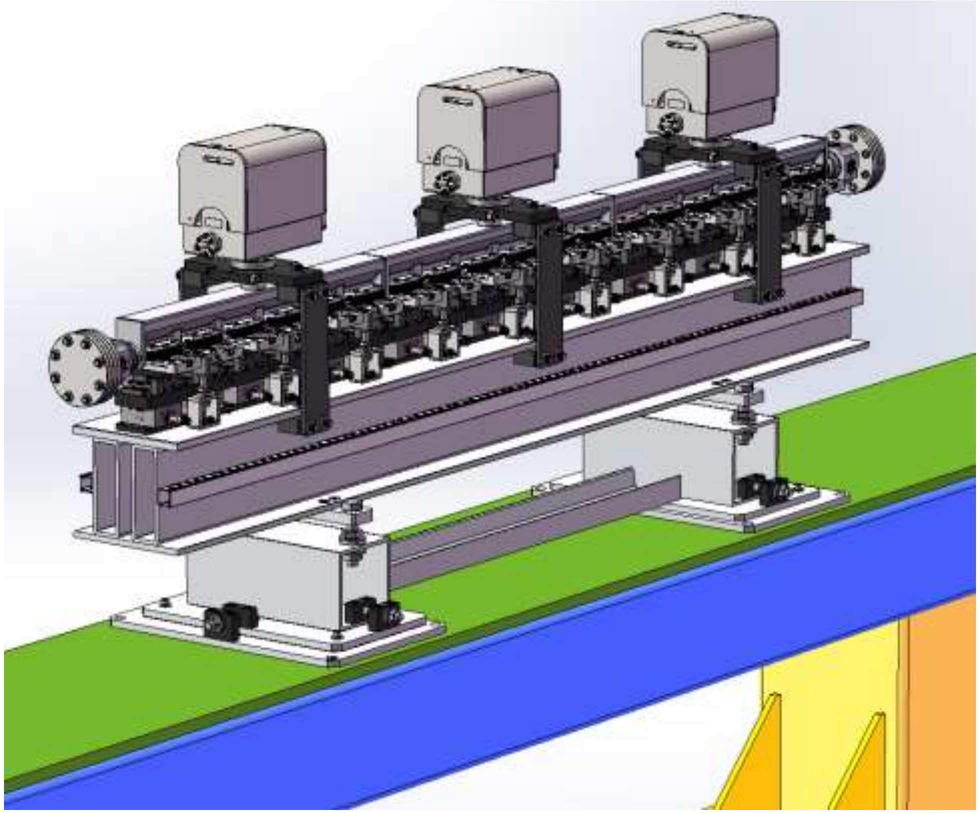
$$\pm\begin{pmatrix}1&0&0&0\\-k&1&0&0\\0&0&1&0\\0&0&-k&1\end{pmatrix}$$

Nonlinear Magnet for Integrable IOTA

- Joint effort with RadiaBeam Technologies (Phase I and II SBIR)



Short prototype built in Phase I



1.8-m long magnet to be delivered in 2016

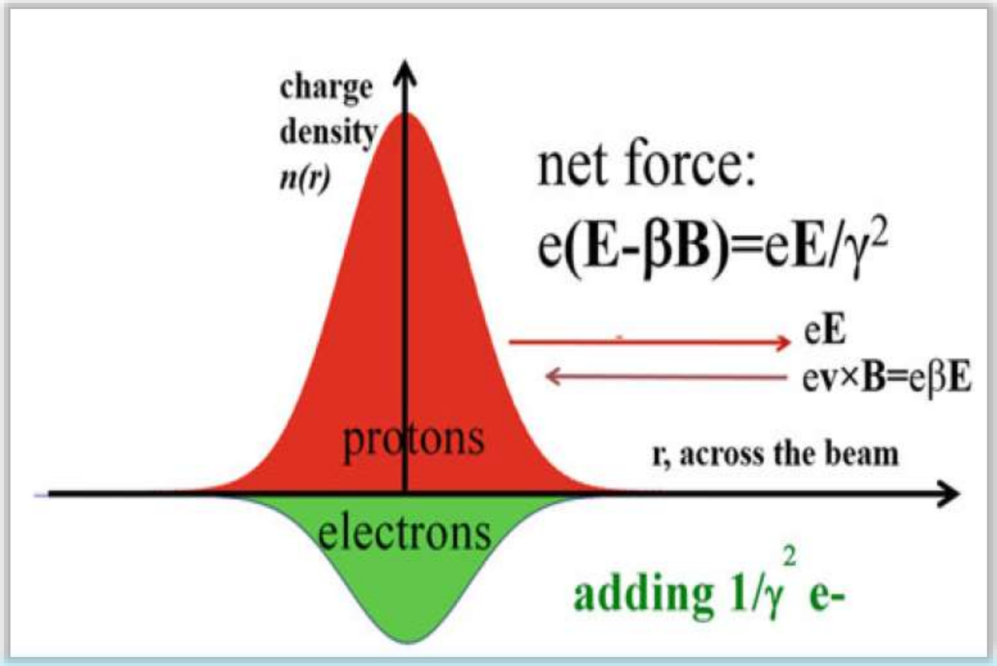
IOTA Research Staging – Phase I (with *e*-)

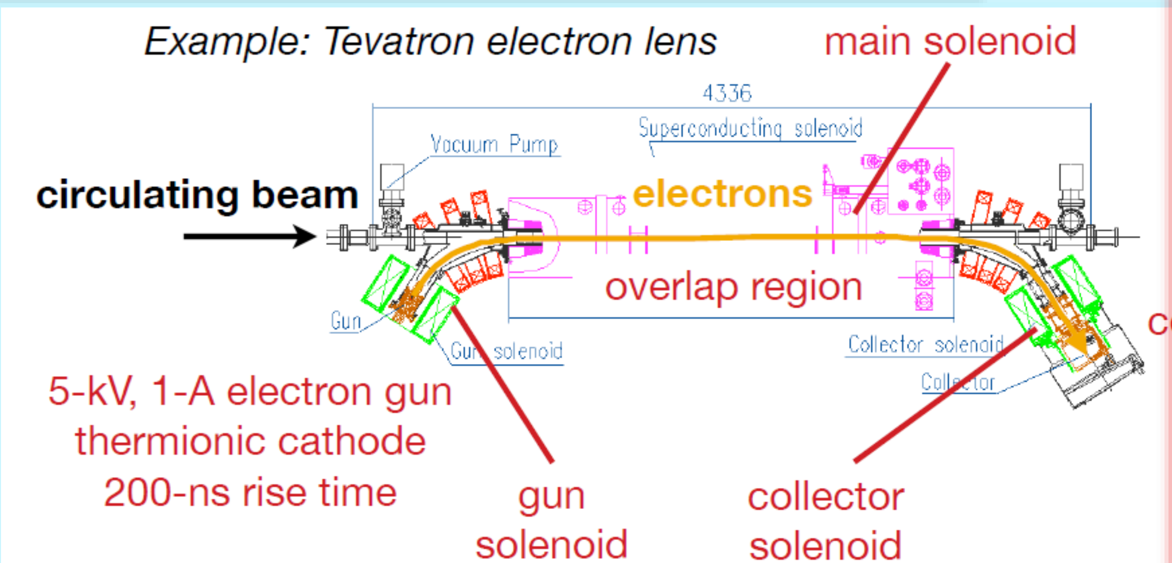
- The magnet quality, optics stability, instrumentation system and optics measurement techniques must be of the highest standards in order to meet the requirements for integrable optics
  - 1% or better measurement and control of β-function
  - and 0.001 or better control of betatron phase
- This is why **Phase I needs pencil *e*$^-$ beams** as such optics parameters are not immediately reachable in a small ring operating with protons

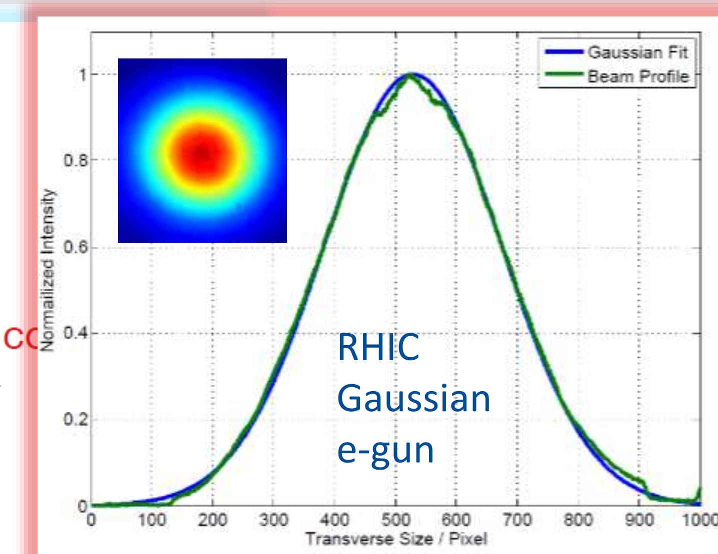
IOTA Parameters

Nominal momentum	***e***$^-$**: 150 MeV/c** ***p+*****: 70 MeV/c**
Nominal intensity	e^-: 1×10^9, p+: 1×10^{11}
Circumference	**40 m**
Bending dipole field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum b-function (x,y)	12, 5 m
Momentum compaction	0.02 ÷ 0.1
Betatron tune (integer)	3 ÷ 5
Natural chromaticity	-5 ÷ -10
Transverse emittance r.m.s.	*e*$^-$: 0.04 μm *p+*: 2μm
SR damping time	0.6s (5×10^6 turns)
RF V,f,q	e^-: 1 kV, 30 MHz, 4
Synchrotron tune	e^-: 0.002 ÷ 0.005
Bunch length, momentum spread	e^-: 12 cm, 1.4×10^{-4}

Electron Lenses: Space-Charge Compensation

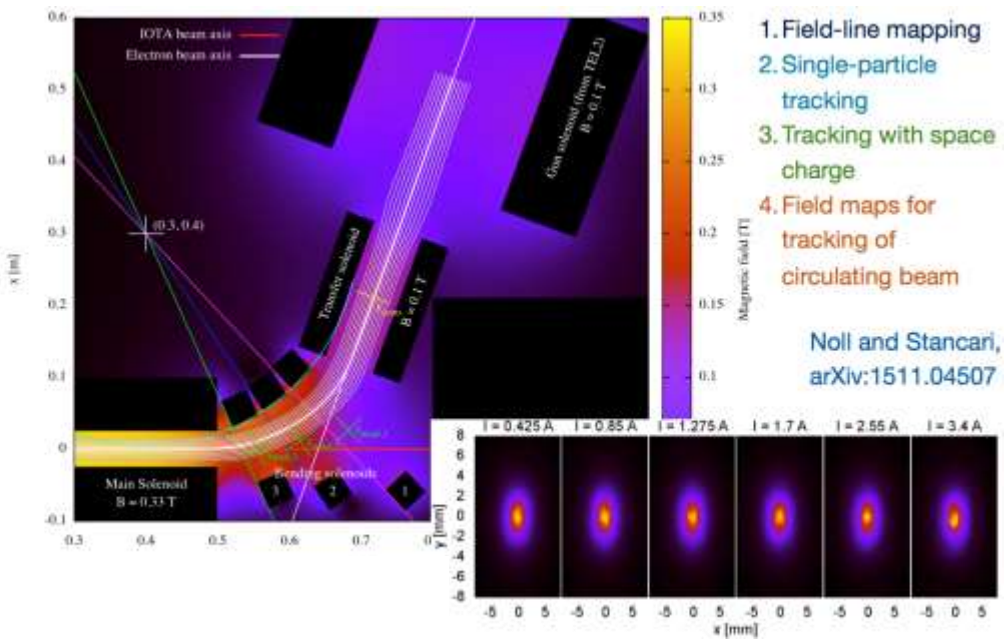






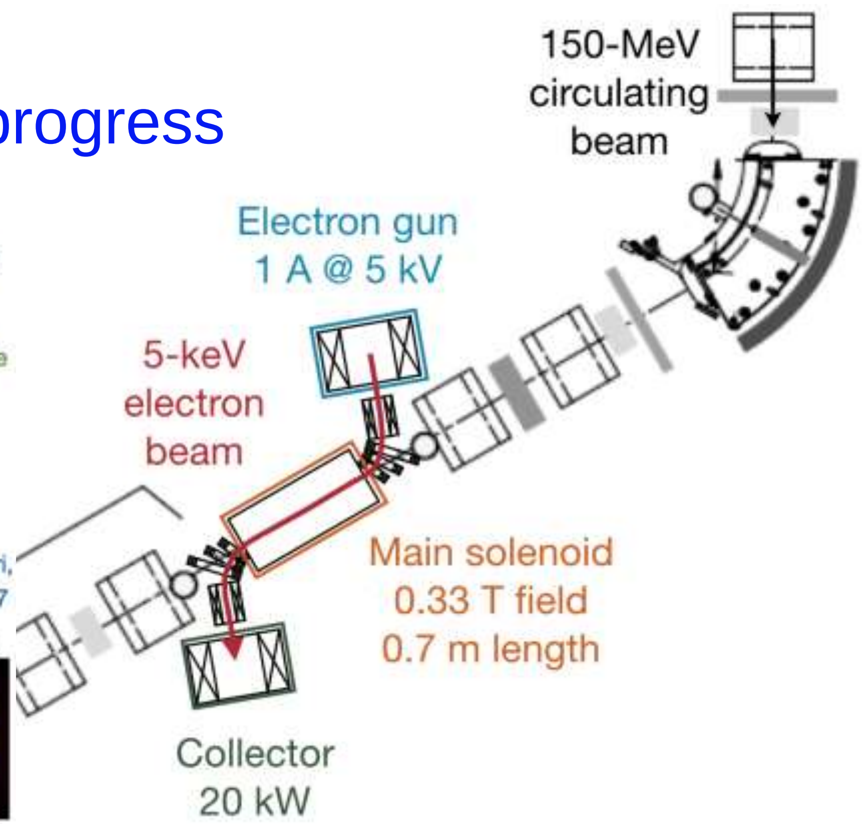
IOTA Electron Lens

- Capitalize on the Tevatron and RHIC experience, LARP work
- Re-use Tevatron Electron Lens components:
  - Removed TEL-2 gun & collector from Tev tunnel
  - Refurbishment in progress
- Computer modeling for IOTA in progress

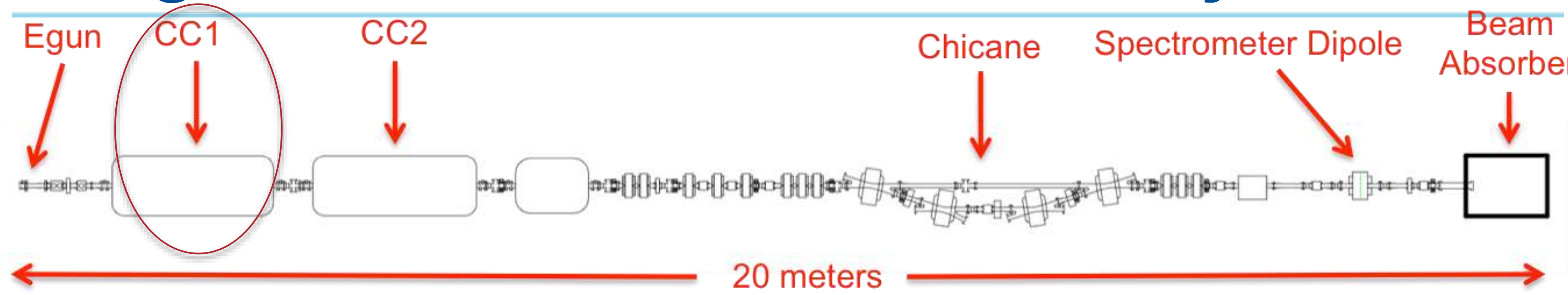


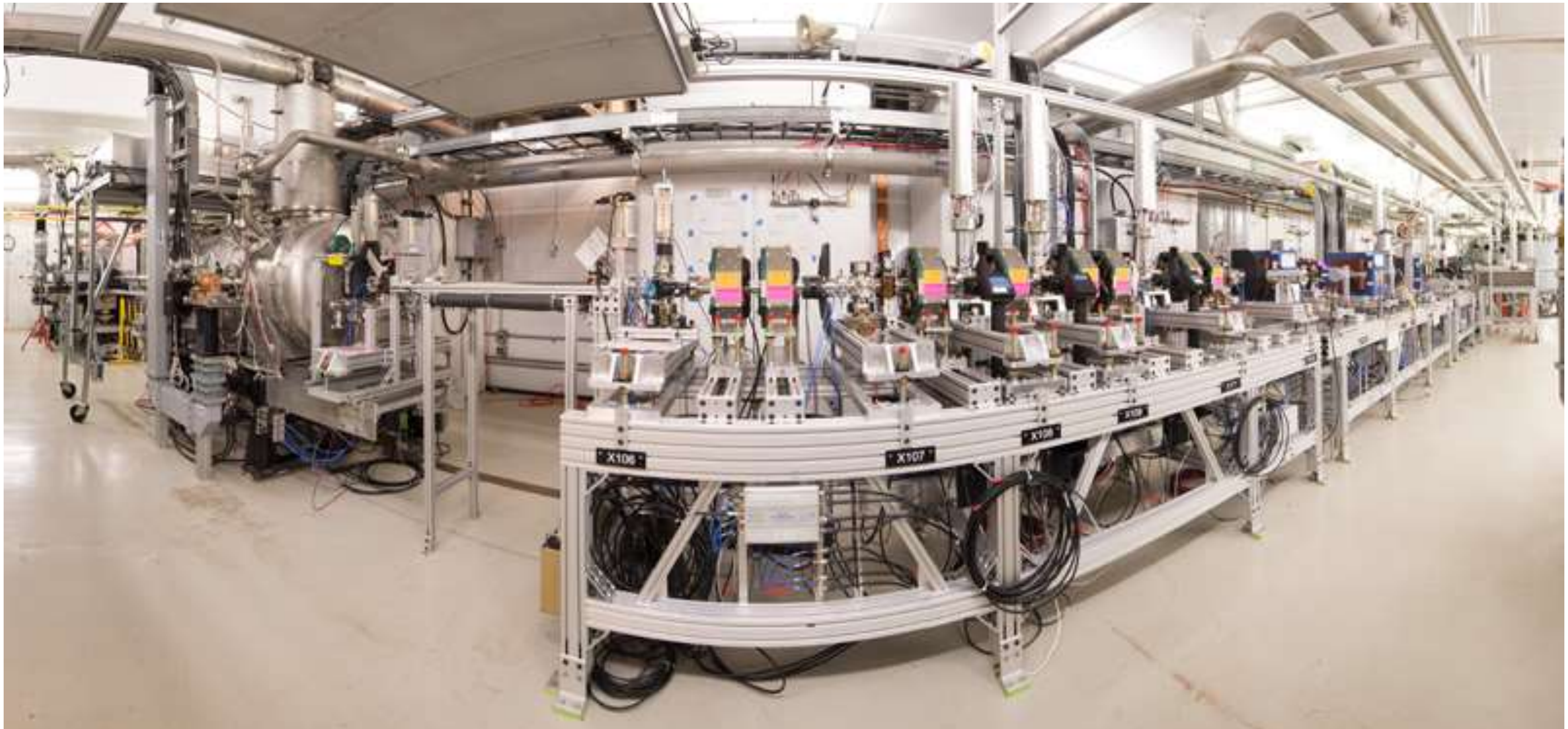
1. Field-line mapping
2. Single-particle tracking
3. Tracking with space charge
4. Field maps for tracking of circulating beam

Noll and Stancari, arXiv:1511.04507



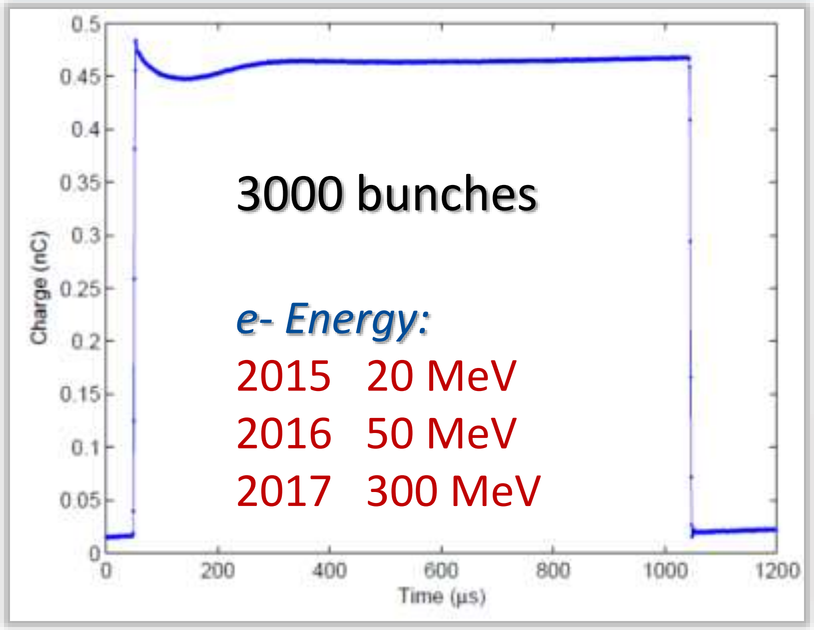
Progress with IOTA Electron Injector





20MeV e^- beam through FAST injector

NB: IOTA *e-* Injector = ILC source



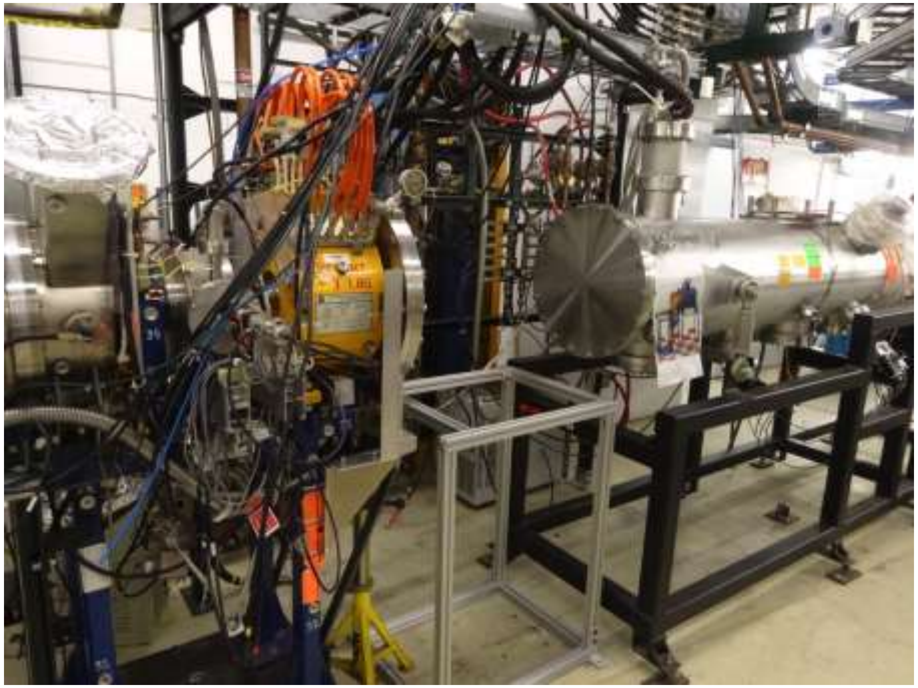
- Example of 3000 pulse-train at a charge of Q_e =0.5nC (operating at 1Hz).
  * we are not able to demonstrate higher Q_e due to the commissioning safety limit
- 5Hz operation of the laser and 1.3 GHz Gun has been established separately.

FAST is unique resource for any (plasma) 1 TeV ILC upgrade R&D

	Now	ILC
Bunch charge	0.5 nC *	3.2 nC
Bunch train	1 ms	1 ms
Bunches/train	3000	3000
Rep.rate	1 Hz *	5 Hz

2015 Progress on IOTA Proton Injector

2.5 MeV Proton RFQ re-commissioning began:



- Ion source separated from RFQ in preparation for instrumentation.
- All parts requisitioned for refurbishment
- On track to re-commission in Q2 FY2016

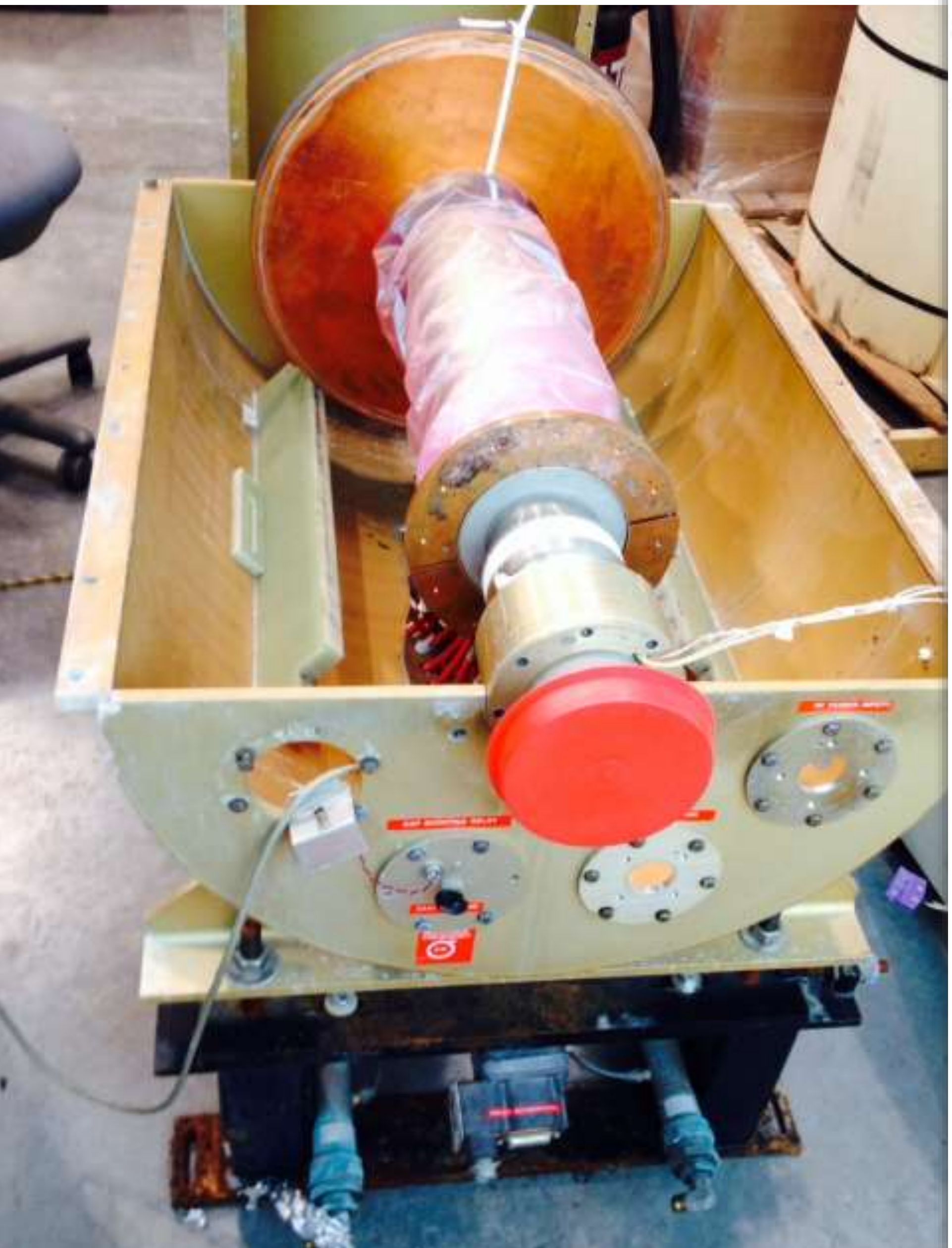
- Reconnected 325 MHz klystron to waveguide and coax.
- Continuing reconnection to RFQ
- On track to deliver beam in Q2-Q3 of FY2016

IOTA Ring: ~50% of All Components in Hand

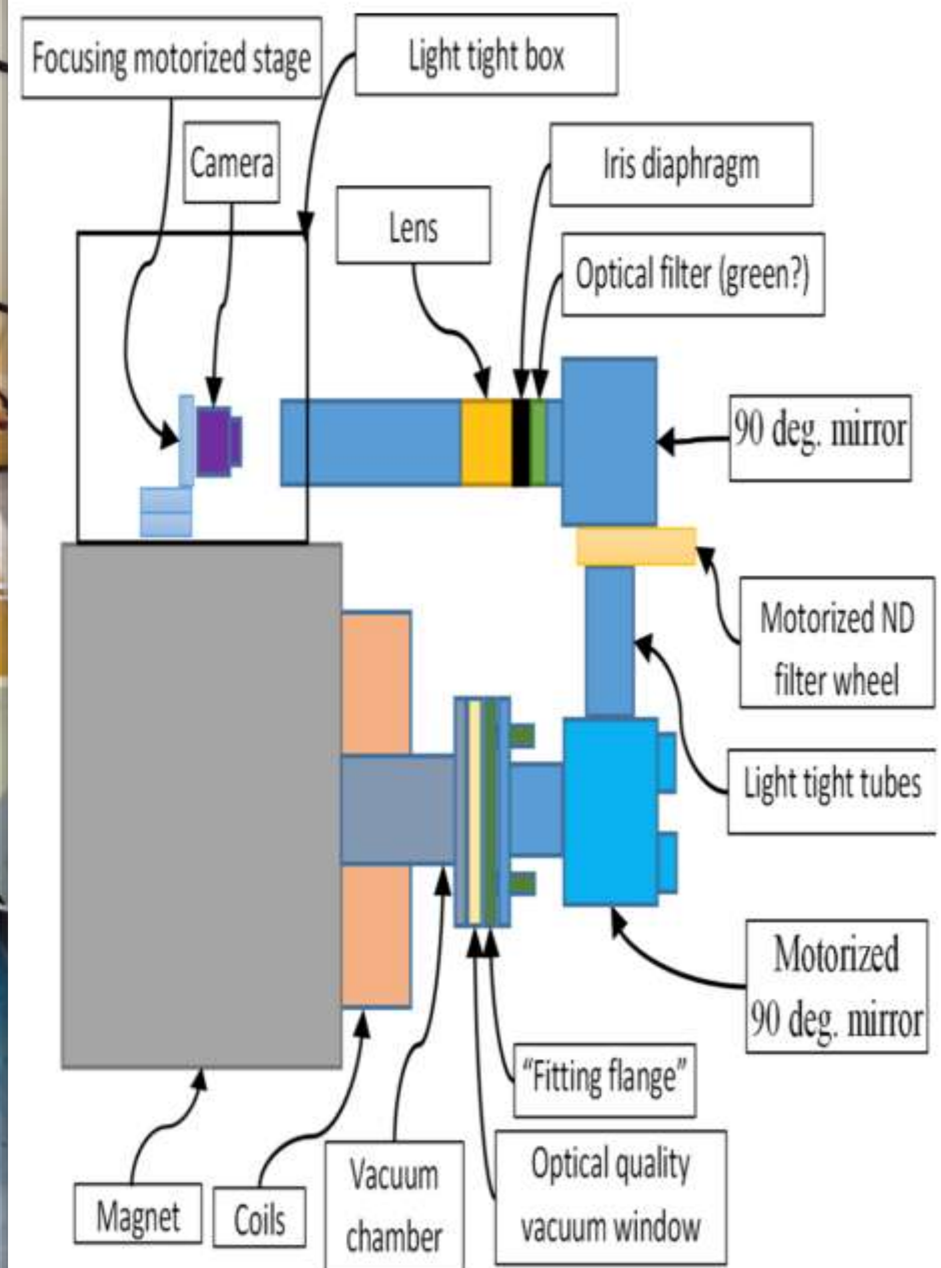
32 IOTA ‘Dubna’ quadrupoles
- being measured in TD

10 more being built

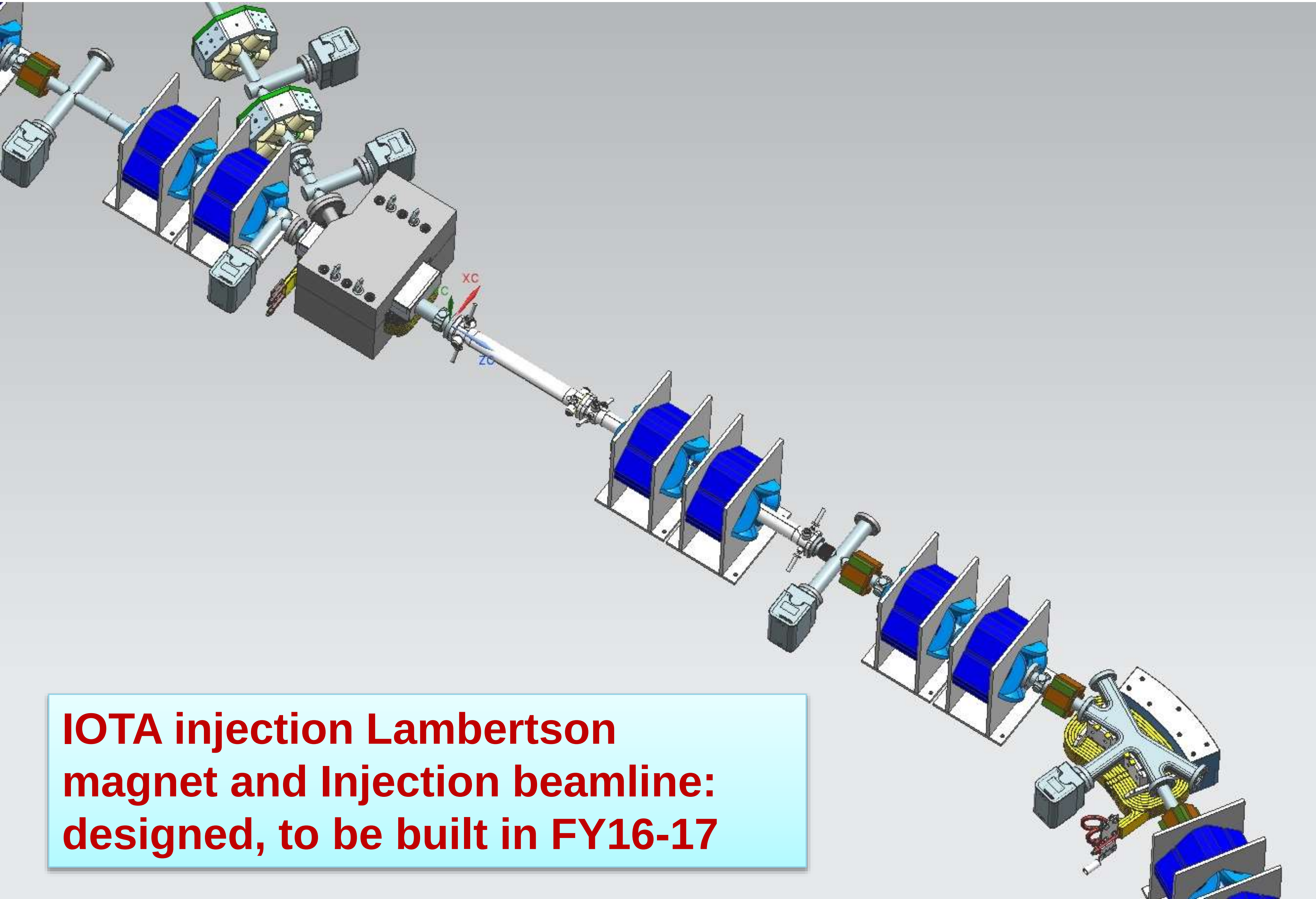
1st IOTA 30-deg. Dipole
9 more ready to ship
(from China)



Pbar RF cavity refurbished for IOTA



IOTA Synchrotron Radiation Monitors



IOTA injection Lambertson magnet and Injection beamline: designed, to be built in FY16-17

High Energy Beamline and Enclosure (FY16)

IOTA Construction and Research Timeline

	Electron Injector	Proton Injector	IOTA Ring
FY15	20 MeV *e*- commiss'd beam tests	Re-assembly began @MDB	50% IOTA parts ready
FY16	50 MeV *e*- commiss'd beam tests	50 keV *p+* commiss'd	IOTA parts 80+% ready
FY17	150-300 MeV *e*- beam commissioning/tests *	2.5 MeV *p+* commiss'd beam tests @ MDB	IOTA fully installed first beam ? *
FY18	*e*- injector for IOTA + other research	*p+* RFQ moved from MDB to FAST *	IOTA commiss'd with *e*- **Research starts (NL IO)**
FY19	*e*- injector for IOTA + other research	2.5 MeV *p+* commiss'd beam tests	**IOTA research with *e*-** IOTA commiss'd with *p+*
FY20	*e*- injector for IOTA + other research	*p+* injector for IOTA	**IOTA research with *p+****

* contingent on $$: FY17-20 - under current budget scenario, explore options to accelerate start of research by 1 year

IOTA Scientific Research Collaboration

- **24 Partners:**
  - ANL, Berkeley, BNL, BINP, CERN, Chicago, Colorado State, IAP, FNAL, Frankfurt, JINR, Kansas, LANL, LBNL, ORNL, Maryland, Michigan State, Northern Illinois, Oxford, RadiaBeam Technologies, RadiaSoft LLC, Tech-X, Tennessee, Vanderbilt

FOCUSED WORKSHOP ON SCIENTIFIC OPPORTUNITIES IN IOTA

https://indico.fnal.gov/conferenceDisplay.py?confId=10547

28-29 April 2015 *Wilson Hall*

US/Central timezone

- By invitation only: 40 participants, 30 not from Fermilab
  - White Paper drafted
- ~25 presentations
- Three Working Groups

S.Chattopadhyay
Workshop Chair

Nonlinear Dynamics (ND) and Space Charge (SC)

KISHEK, Rami (CHAIR)
SHILTSEV, Vladimir (CO-CHAIR)

Optical Stochastic Cooling (OSC) and Single Electron Quantum Optics (SEQO)

ZHOLENTS, Alexander (CHAIR, OSC)
KIM, Kwang-Je (CO-CHAIR, OSC and SEQO)
SHAFTAN, Timur (CO-CHAIR, SEQO)

Emittance Exchange (EE) , Radiation (R) and Laser-Beam Shaping (LBS)

WURTELE, Jonathan (CHAIR)
THANGARAJ, Jayakar (CO-CHAIR)

IOTA Research: Beam Physics Drivers

1. **Nonlinear Integrable Optics** – Experimental demonstration of Non-linear Optics lattice in a practical accelerator
2. **Space Charge Compensation** – Suppression of SC-related effects in high intensity circular accelerators
   – Nonlinear Integrable Optics
   – Electron lenses
   – Electron columns
   – Circular betatron modes
3. **Beam collimation** – Technology development for hollow electron beam collimation

GARD

Collaborators

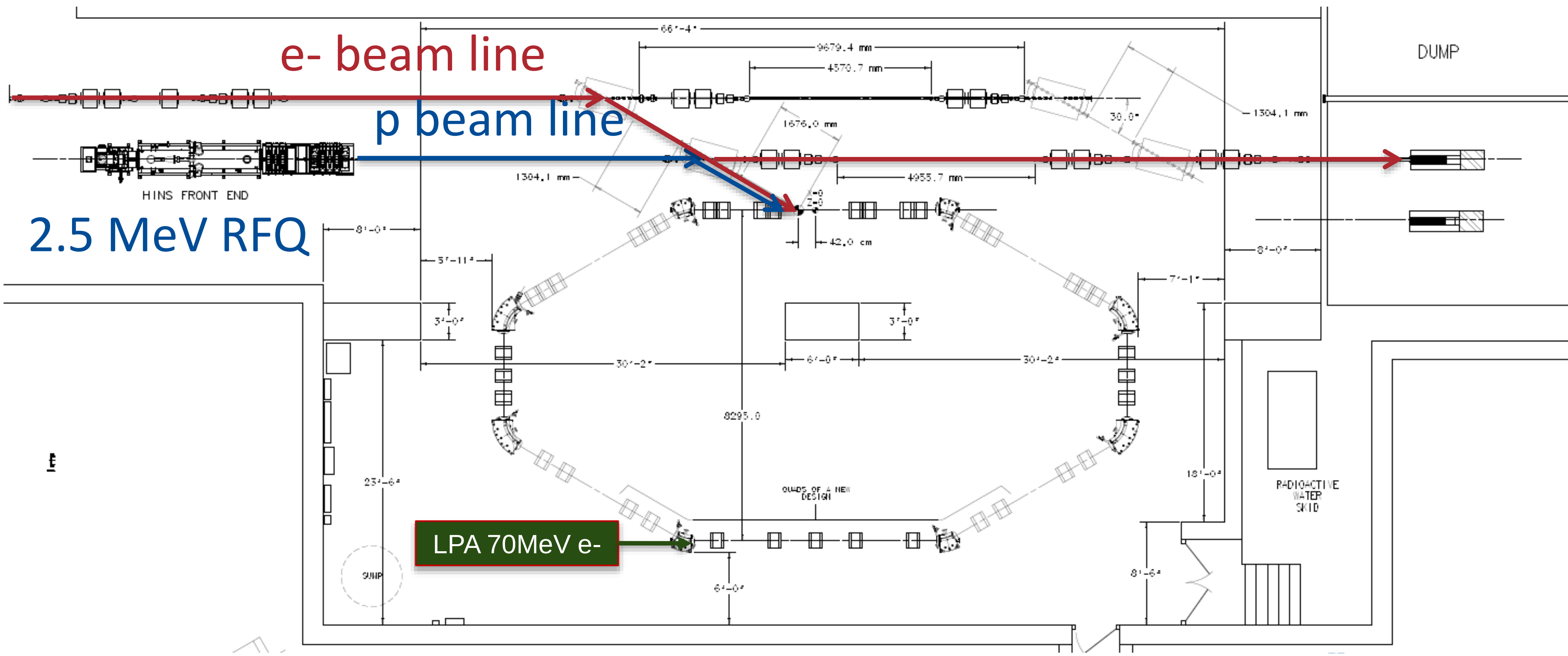
under discussion by collaborators:

- **Optical Stochastic Cooling** – Proof-of-principle demonstration
- **Electron Cooling** – Advanced techniques
- **Laser-Plasma Accelerator** – Demonstration of injection into synchrotron
- **Quantum Physics** – Localization of single electron wave function

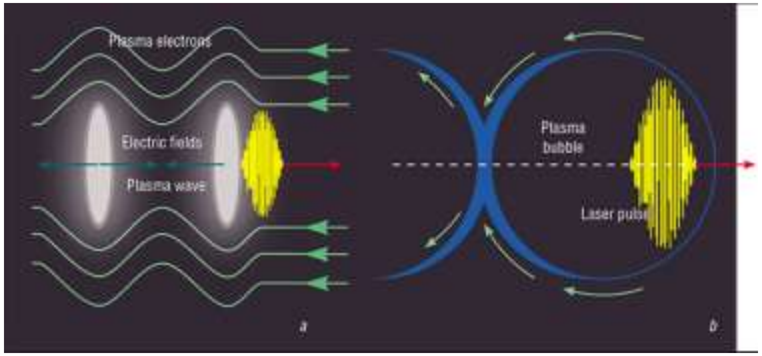
Collaborators

(Dream of) LPWA *e-* Injector for p+ IOTA Tune Up

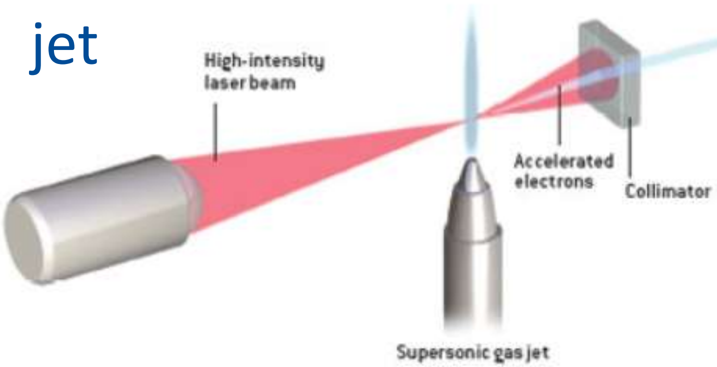
- Given expected sensitivity of the Integrable Optics and Space-Charge Compensation to the lattice imperfections, it is very desirable to have an option of reverse *e-* injection to tuneup IOTA optics for record high tune-shift operation with 70 MeV/c protons
- Need compact 70 MeV electron source – e.g., LPWA

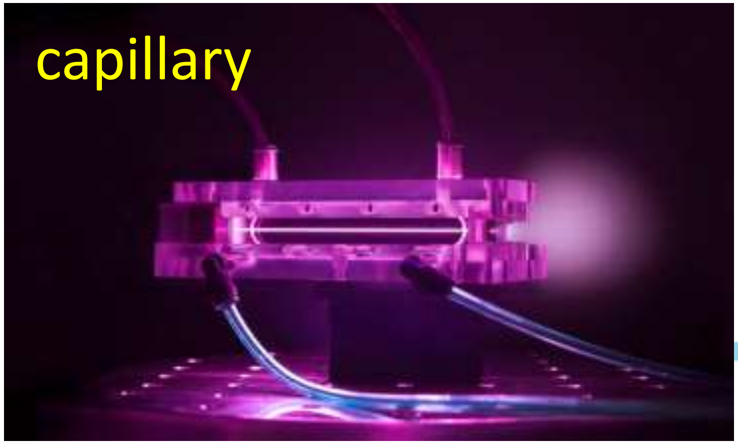


Laser Wakefield Acceleration Injector for IOTA ?



jet





Main Specs:

e- Energy	70 MeV
Bunch charge	(¼ - ½) nC
Rep.rate	~0.1 Hz
E spread d*E/E*	< 0.2%
Emittance, n-rms	< 100 µm

Important Considerations:

- Compact (<1 m)
- Injection (matching, on orbit?, kicker?)
- Cost (low)
- Reliability and stability (high)

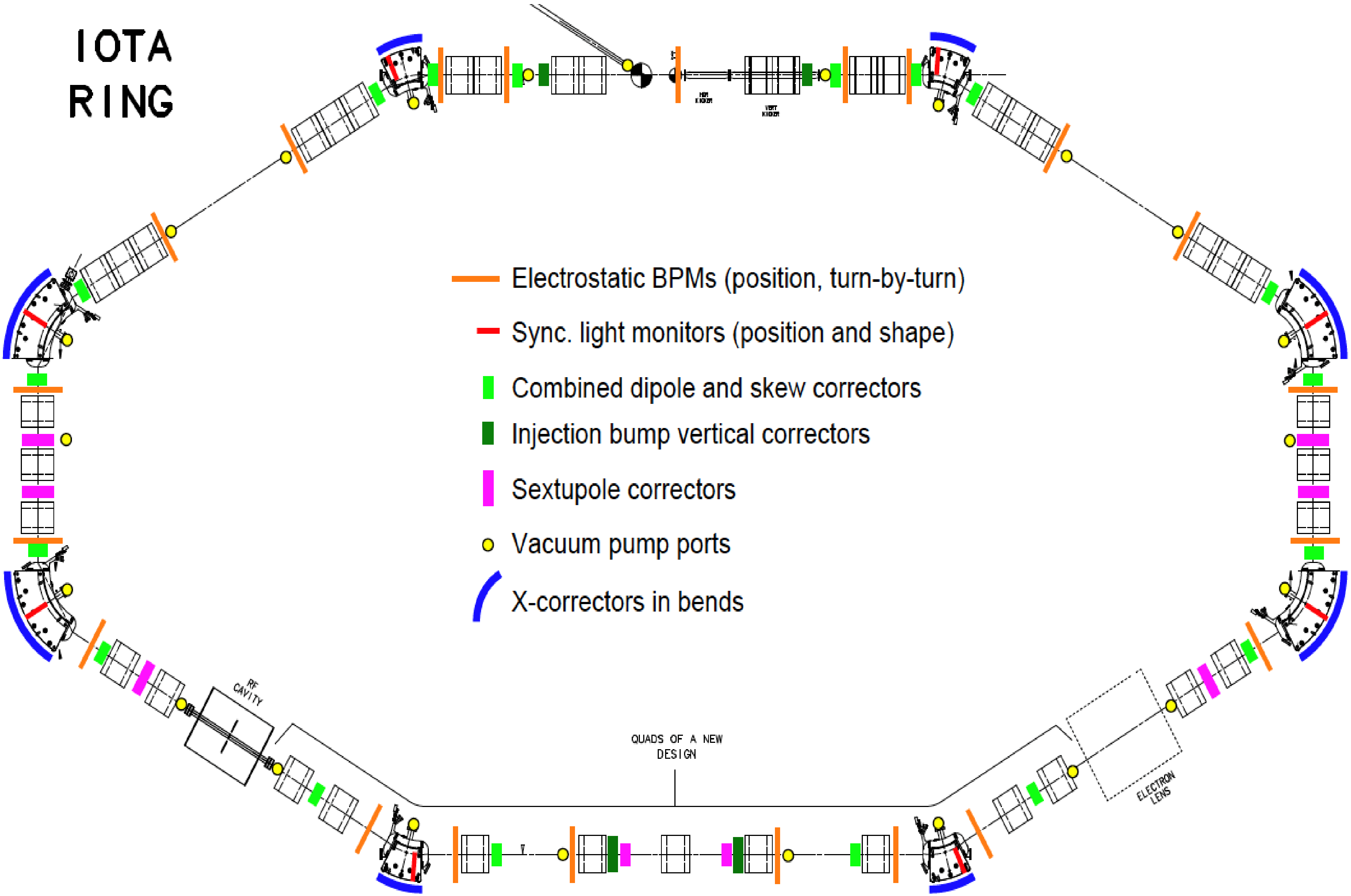
This would be the first occurrence of the laser wakefield method used as an electron source for injection into an operational accelerator.

Summary

- **IOTA Ring at the FAST is (going to be) the leading Accelerator R&D facility for the Intensity Frontier HEP**
  - OHEP GARD thrust: Accelerator and Beam Physics
- **Progressing - construction, commissioning, research :**
  - *e*- injector operational @ 20MeV (50 MeV in 2016, >150MeV in 2017)
  - >50% of IOTA parts in hand, *1st beam in IOTA ca. 2017*
  - *p*+ injector readiness in *ca.* 2019 (depends on support)
  - Integrable Optics and Space Charge Compensation experiments are being prepared, many collaborators *(you're welcome!)*
- IOTA is valuable resource for the future LC community:
  - ILC-type electron source (up to 300 MeV)
  - (Aspiration for) 70 MeV PWFA e- injector after 2020

Back up slides

IOTA Layout



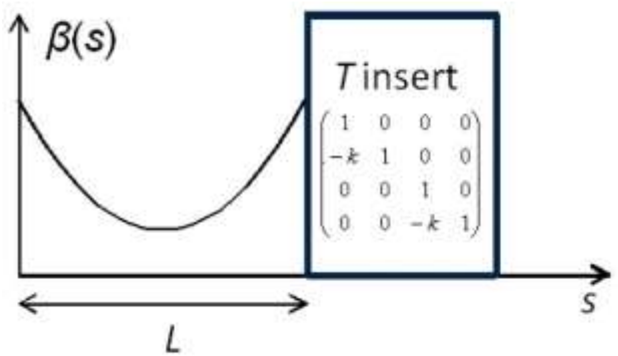
IOTA
RING
Electrostatic BPMs (position, turn-by-turn)
Sync. light monitors (position and shape)
Combined dipole and skew correctors
Injection bump vertical correctors
Sextupole correctors
Vacuum pump ports
X-correctors in bends
RF CAVITY
QUADS OF A NEW DESIGN
ELECTRON LENS

Nonlinear Integrable Optics with Laplacian Potential

1 Start with a round axially-symmetric *linear* lattice (FOFO) with the element of periodicity consisting of

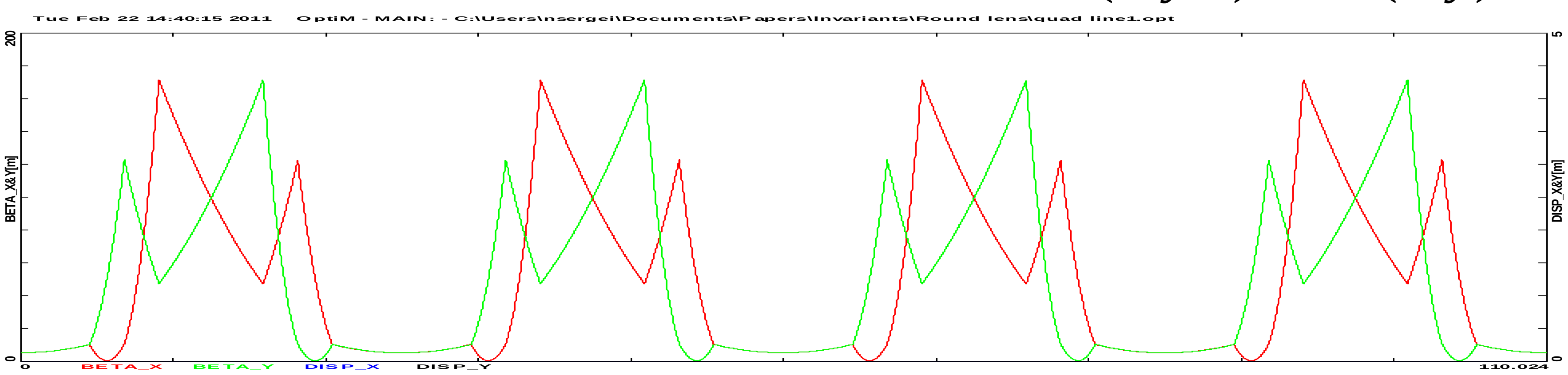
a. Drift L

b. Axially-symmetric focusing block "T-insert" with phase advance n × π

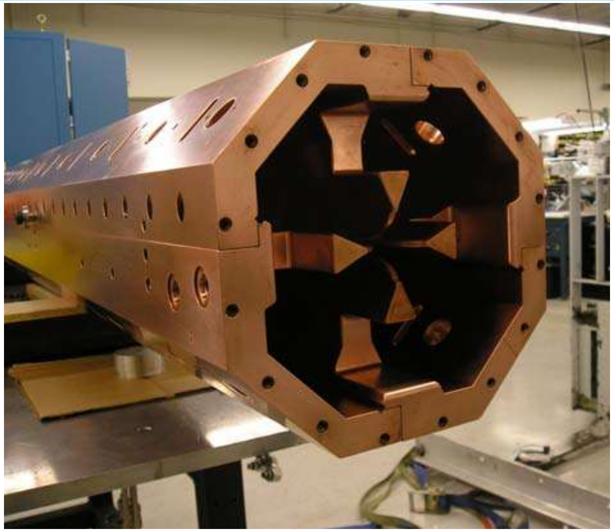


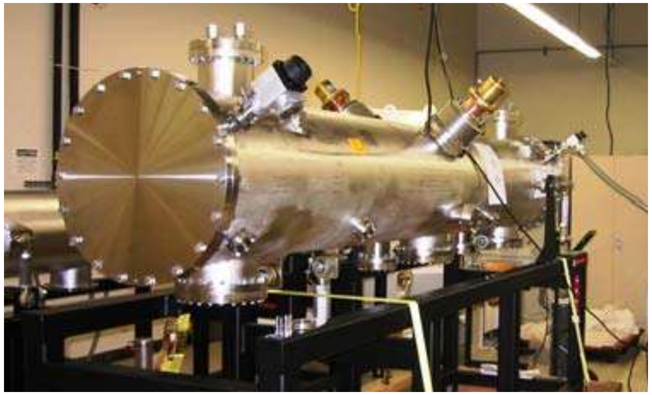
1 Add special nonlinear potential *V(x,y,s)* in the drift such that

$$\Delta V(x, y, s) \approx \Delta V(x, y) = 0$$



RFQ Design and Specifications





Pulsed 4-vane RFQ (specs):

Table 1. Initial Specifications for the RFQ Design

Input energy	50 keV
Output energy	2.5 MeV
Frequency, MHz	325
Accelerating beam current, mA	40
Peak surface field, kV/cm	<330
Acceleration efficiency,%	>95
Pulsed power losses in copper, kW	<450
Duty factor, %	1
Total length of vanes	302.428 cm
Average bore radius	3.4 mm
Input rms transverse emittance, normalized π mm mrad	0.25
Transverse emittance growth factor	<1.1
Longitudinal rms emittance, π keV deg	<150
Separation between operating and nearest dipole modes	>4 MHz

HINS Parameters for IOTA

Table 1: HINS Parameters for IOTA

Parameter	Value	Unit
Particle type	proton	-
Kinetic Energy	2.5	MeV
Momentum	68.5	MeV/c
β	.073	-
Rigidity	.23	T-m
RF structure	325	MHz
Current	8	mA
Circumference	39.97	m
Total Protons	9.1×10^{10}	-
RMS Emittance (un-normalized)	4	π-mm-mrad
Tune shift	$-.51 \times B$	-
Pulse rate	<1	Hz
Pulse length	1.77	μsec

matched to IOTA momentum, β=.073

Demonstrated for 1 ms pulses = our baseline. Should go to >40 mA for short pulses.

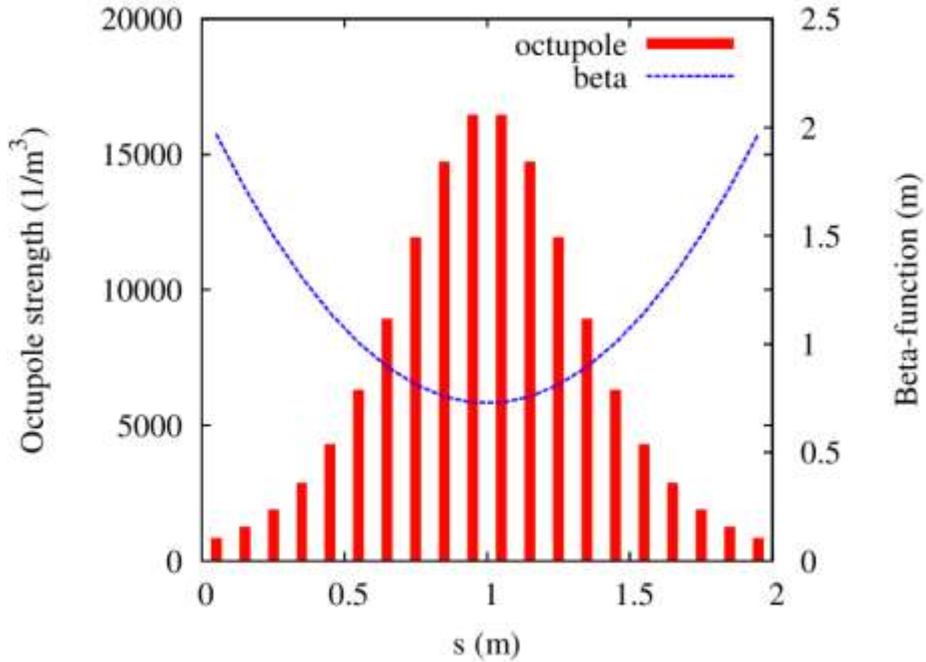
big enough, can do multiple injections if needed later

Quasi-Integrable System

- Build *V* with Octupoles

$$V(x,y,s)=\frac{\kappa}{\beta(s)^3}\left(\frac{x^4}{4}+\frac{y^4}{4}-\frac{3x^2y^2}{2}\right)$$

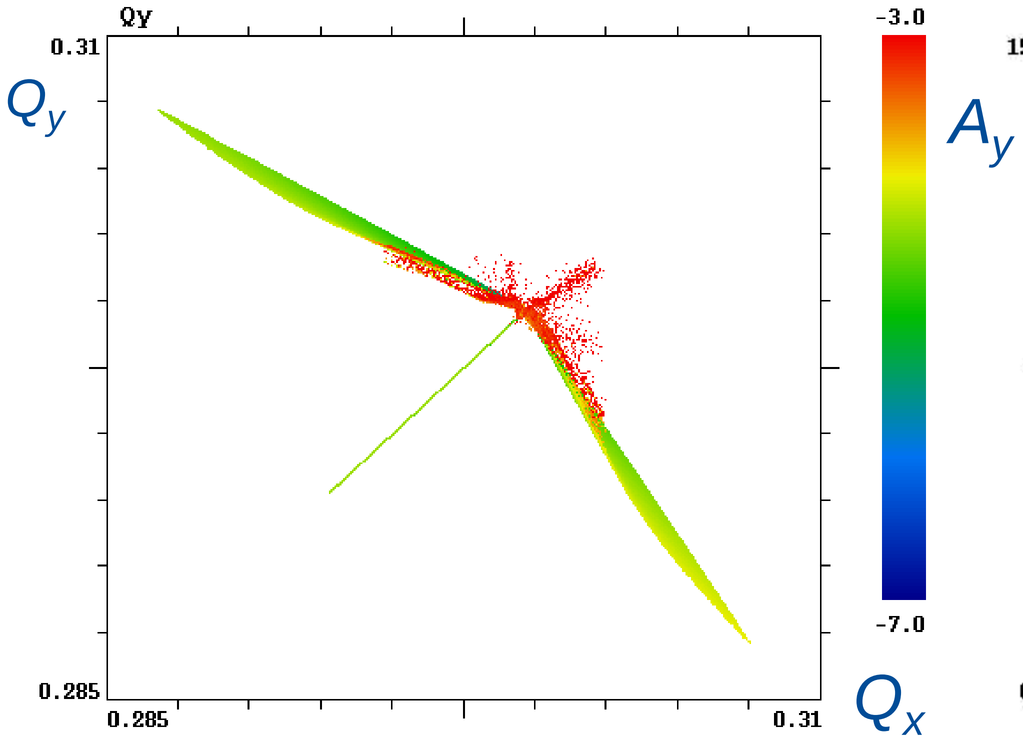
$$U=\kappa\left(\frac{x_N^4}{4}+\frac{y_N^4}{4}-\frac{3y_N^2x_N^2}{2}\right)$$

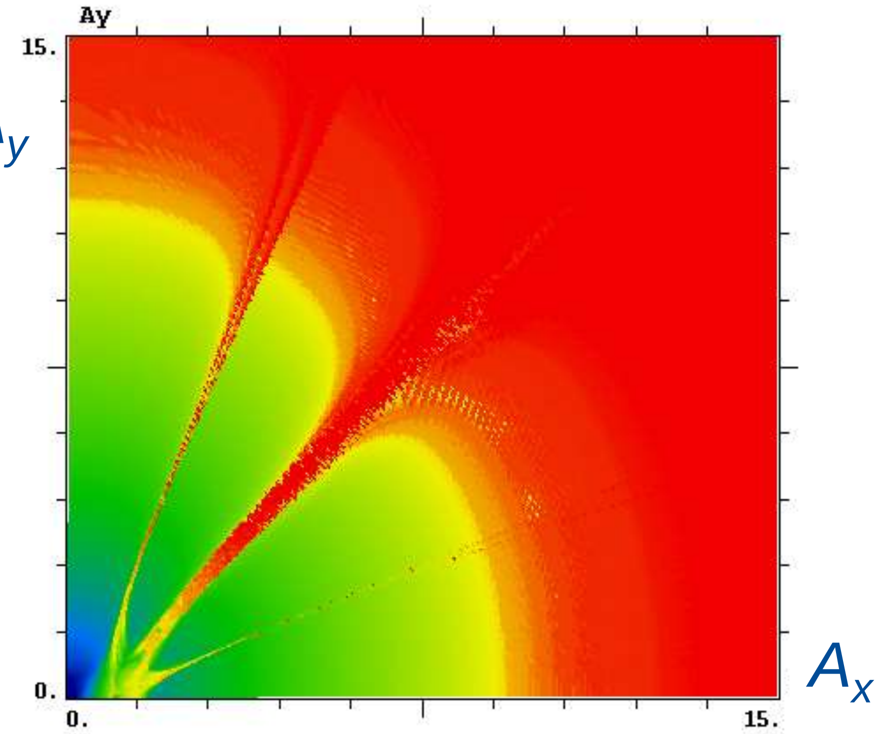


$$H=\frac{1}{2}(p_x^2+p_y^2)+\frac{1}{2}(x^2+y^2)+\frac{k}{4}\left(x^4+y^4-6x^2y^2\right)$$

- Only one integral of motion – *H*
- Tune spread limited to ~12% of Q_0

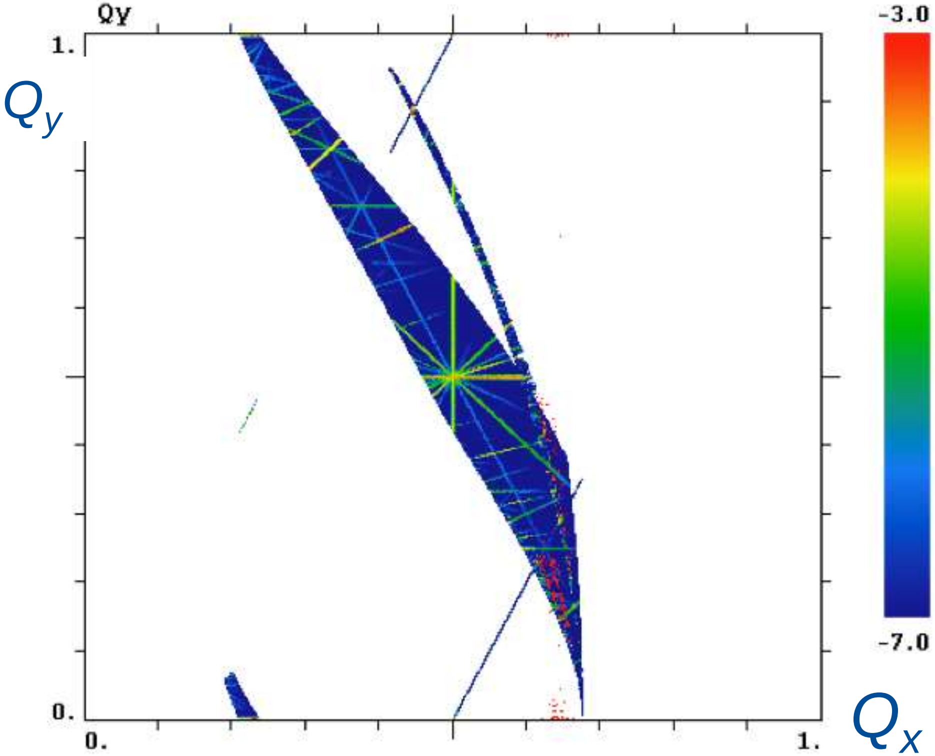
Quasi-Integrable System with Octupoles

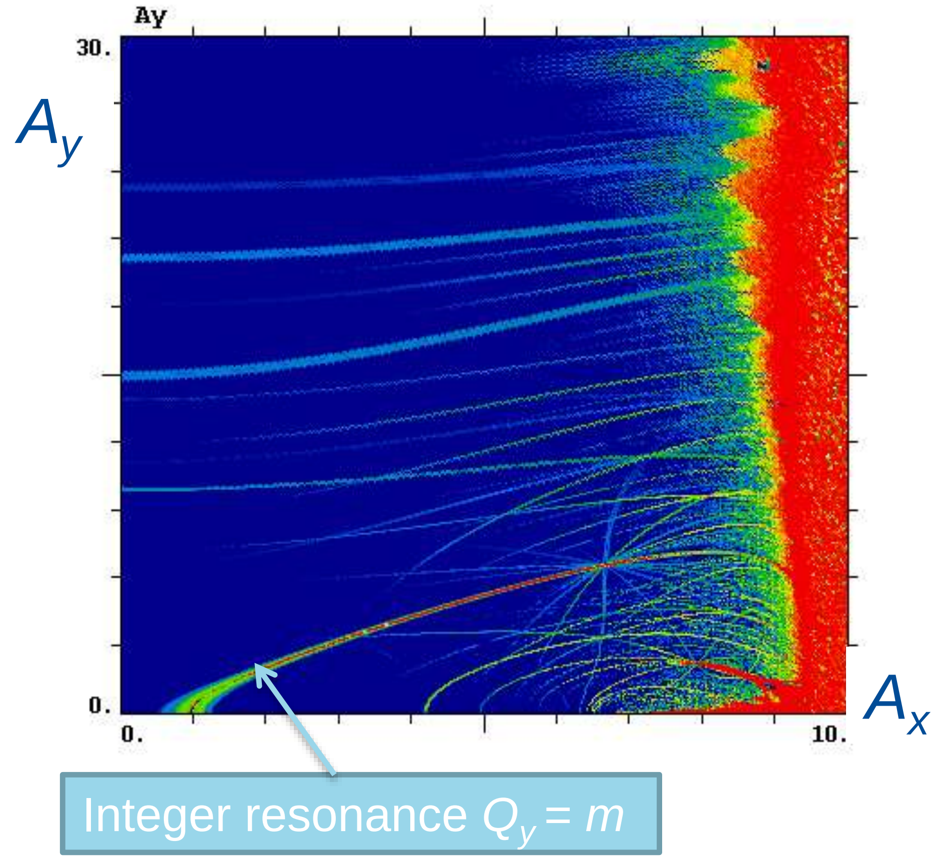




- While dynamic aperture is limited, the attainable tune spread is large ~0.03 – compare to 0.001 created by LHC octupoles

Single Particle Dynamics in Integrable Optics





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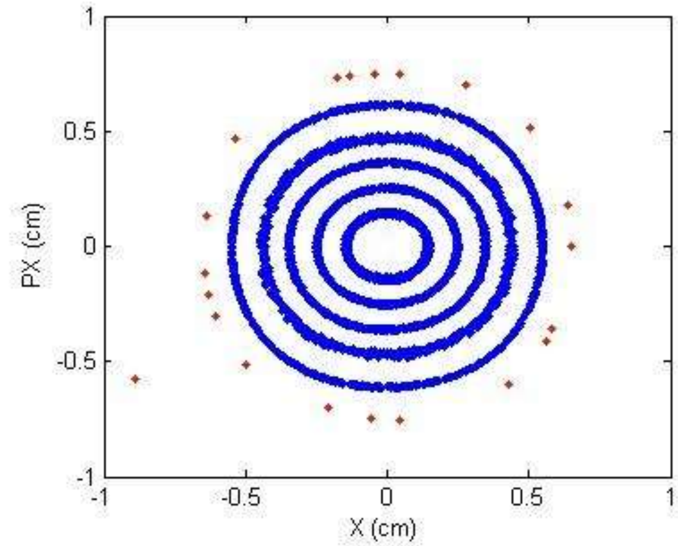
IOTA Staging – Phase I

Phase I will concentrate on the academic aspect of single-particle motion stability using e-beams

- **Achieve large nonlinear tune shift/spread** without degradation of dynamic aperture **by “painting”** the accelerator aperture **with a “pencil” beam**
- Suppress strong lattice resonances = cross the integer resonance by part of the beam without intensity loss
- Investigate stability of nonlinear systems to perturbations, develop practical designs of nonlinear magnets
- The measure of success will be the achievement of high nonlinear tune shift = 0.25

Experimental Procedure

- Two kickers, horizontal and vertical, place particles at arbitrary points in phase space
- Measure beam position on every turn to create a Poincare map



- As electrons lose energy due to synchrotron radiation, they will cover all available phase space
- Can control the strength on the nonlinearity
- Final goal – measure dependence of betatron frequency on amplitude